# Recycling flows in emergy evaluation: A mathematical paradox?

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## Abstract

This paper is a contribution to the emergy evaluation of systems involving recycling or reuse of waste. If waste exergy (its residual usefulness) is not negligible, wastes could serve as input to another process or be recycled. In cases of continuous waste recycle or reuse, what then is the role of emergy? Emergy is carried by matter and its value is shown to be the product of specific energy with mass flow rate and its transformity. This transformity ($\tau$) given as the ratio of the total emergy input and the useful available energy in the product (exergy) is commonly calculated over a specific period of time (usually yearly) which makes transformity a time dependent factor. Assuming a process in which a part of the non-renewable input is an output (waste) from a previous system, for the waste to be reused, an emergy investment is needed. The transformity of the reused or recycled material should be calculated based on the pathway of the reused material at a certain time (T) which results in a specific transformity value ($\tau$). In case of a second recycle of the same material that had undergone the previous recycle, the material pathway has a new time ($T+T_1$) which results in a transformity value ($\tau_1$). Recycling flows as in the case of feedback is a dynamic process and as such the process introduces its own time period depending on its pathway which has to be considered in emergy evaluations. Through the inspiration of previous emergy studies, authors have tried to develop formulae which could be used in such cases of continuous recycling of material in this paper. The developed approach is then applied to a case study to give the reader a better understanding of

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the concept. As a result, a 'factor' is introduced which could be included on emergy evaluation tables to account for subsequent transformity changes in multiple recycling. This factor can be used to solve the difficulties in evaluating aggregated systems, serve as a correction factor to up-level such models keeping the correct evaluation and also solve problems of memory loss in emergy evaluation. The discussion deals with the questions; is it a pure mathematical paradox in the rules of eMergy? Is it consistent with previous work? What were the previous solutions to avoid the cumulative problem in a reuse? What are the consequences?

***Keywords:*** **Emergy; Recycle; Wastes; Transformity; Sustainability**

## 1.0 Introduction

Emergy synthesis has been widely applied in the evaluation of ecological systems, energy systems, and environmental impacts of processes and a large number of studies. Most studies have applied the emergy theory to eco-economic systems in recent years. Brown and Ulgiati (2002) proposed an emergy-based method to quantitatively study the function of the environment in absorbing and diluting by-products generated by a process. Bakshi (2000) introduced an emergy analysis method for industrial systems, where waste treatment was considered. The wastes are not only handled by an end-of-pipe treatment approach and ecosystem dilution, but also by waste reuse techniques. Yang et al. (2003) also proposed a new emergy analysis method for waste treatment, reuse and recycle. Recycling is a major concept in completing the ecological life cycle of materials, where waste or production output from one system is an input to another system. Recycling serves to amplify and reinforce production processes, and provides a multiplier to the input resources. Systems that do not develop a complete cycle of materials will not be long continued (Odum, 1996; Buranakarn, 1998).

Recycling is a common vocabulary when dealing with waste. Ulgiati et al. (2004) observe that emergy indeed has a role in this terminal part of the process chain and propose ways of accounting for its emergy amounts to avoid mistakes when recycling waste. If the wastes are released into the environment, the input provided by nature for their abatement via natural processes should be accounted for and assigned to the main product. However if wastes are treated and re-enter a production process as a substitute material or resource, only the emergy invested in the treatment and recycling process should be assigned to the recycled resources. A set of indices based on emergy for the evaluation of such sustainable processes and economics (Brown and Ulgiati, 1997), is used in evaluating the recycling value of solid wastes. The concept of emergy has been also applied to building construction and recycle of building materials and several environmental indicators have been proposed (Buranakarn, 1998; Brown and Buranakarn, 2003; Huang and Hsu, 2003; Meillaud et al., 2005; Pulselli et al., 2008; Yuang et al., 2008). For example, Buranakarn (1998) made emergy calculations for recycling matter in building applications where he studied 4 material flows and recycling patterns based on emergy evaluation:

1. conventional material flow where material is discarded after use
2. material recycle where material is recycled back to a stage in the transformation process and re-transformed
3. use of a by-product waste from another production process in place of some material
4. reuse of a material for some other purpose

In this case study (Buranakarn, 1998) the author considered the effect of material recycle in calculating its transformity for a first recycle. Most studies usually consider solid wastes recycling as one system with a single output (Machettini et al., 2007; Feng and Cao, 2007; Brown and Buranakarn, 2003). Some studies however, consider the recycling system as a multi-product system (Yang et al., 2003). Solid wastes could either be beneficial or not depending on the process under study. Two different kinds of wastes are normally observed in eco-economic systems. One serves as a potential resource to produce new goods whilst the other is the real waste with no potential for any resource recovery (Yuang et al., 2008). When the wastes are fully degraded so that the useful value of whatever their physical characteristics (concentration, pressure, chemical potential, temperature) is zero in relation to the reference level of the environment, they are no longer a resource (Ulgiati et al., 2004). These real wastes need resources and services to render them harmless. When comparing recycling pathways with traditional waste treatment, it is important to consider these two kinds of wastes at the same time (Yuang et al., 2008). However, some researchers focus on the harmful waste (Bastianoni et al., 2002; Yang et al., 2003; Lou, 2004) and neglect the resourceful waste which could be a resource for new products and accounted for as emergy inflows.

This work contributes to a better accounting of emergy for recycling processes. A set of equations are proposed with a correction factor and used in some examples (metallic products - steel and aluminium recycling processes and non metallic products – glass and plastic recycling processes).

## 2.0 Emergy evaluation for systems involving recycling flows

Consider an aggregated system as in fig 1. With a raw material flow (Source A), into the system, not all internal processes might be known within the different process units (Brown and Ulgiati, 2004). In this example, raw materials are refined, transformed, used and discarded. Source (B) represents the flow from other services, goods and fuel. As such, the process of refining requires an emergy input ($E_R$). The process of transforming the refined material into a finished product also requires emergy inputs of fuels, goods and services ($E_T$). If the emergy in the raw material is $E_M$ then the emergy in the product ($E_P$) is the sum of the emergy in the raw materials and the emergy inputs for refining and transformation i.e. $E_P = E_M + E_R + E_T$

Fig. 1. Aggregated system with no internal recycle flows

Considering a similar system which involves recycling, additional emergy through services, goods and fuel inputs would be required for recycling ($E_c$) from source (C) as shown in fig 2. The emergy in the product ($E_P$) is then the sum of the emergy in the raw materials and all the emergy inputs required to maintain the cycle of the material system i.e. $E_P = E_M + E_R + E_T + E_C$ (Note: though $E_M$ remains the same notation for both the conventional process and the recycling process, they vary in terms of real quantities i.e. $E_M$ decreases since $E_c$ is a substitute in the recycling scenario).

Fig. 2. Aggregated system with recycle flows

The transformity of the product is given as: $\tau_P = \frac{\sum_{source} E_i}{Q}$ which takes into account the individual emergy flows ($E_M$, $E_R$, $E_T$, $E_c$) over a year and the product output ($Q$). Transformity (of raw material, fuels, goods, services, and so on…) is undoubtedly an important concept in emergy studies. There is still an on going research in developing the use of transformity values and its use in emergy evaluation (Ingwersen, 2010; Baral and Bakshi, 2010; Amponsah and Le Corre, 2010; Ulgiati et al., 2010 etc).

Systems with recycling flows as mentioned above have a rather peculiar nature. The additional emergy ($E_c$) needed by a system involving recycling or material reuse obviously increases the output or final emergy compared to that of a conventional system. As such, a new transformity would be defined by this system involving recycle.

## 3.0 Analysis Method

In fig. 3 the method of configuring a general equation for systems with recycling flows, is described for a unitary product. As such, the kind or units of material input is not significant.

Fig. 3. Opening out the time notion for emergy evaluation of recycling process (a loop layer order)

Where $E_i$ is the total emergy inputs (emergy of raw material, fuel, goods and services etc without recycle, from source (A) and (B)), $E_c$ is the specific additional emergy needed for recycling from source (C), ($E_c$ is calculated from the emergy of the additional activities needed before a material is successfully recycled or reused (e.g. sorting and collection). The total emergy of $E_c$ is dependent on the fraction of material recycled, $q$). $E_P$ is the specific emergy in the product, $q$ is the fraction or percentage of material (product) to be recycled and $t$ is the additional time needed for recycling. From fig. 3, it is therefore clear that in the first case, there is no recycle operation i.e. $t_0$ and $q$=0; $E_c$=0.

$$E_P(0)=E_i(0) \tag{1}$$

However, in the first recycle, if $q(1)$ is the quantity to be recycled and $t_1$ indicates the recycle time, it must be noted that it already contains a specific emergy from the previous operation that led to its formation given as $E_P(0)q(1)$. Also, the additional specific emergy needed for the current recycling (collection, sorting etc.) is given as $E_c(1)q(1)$ and the specific emergy of the new raw material for the process, given as $E_i(1)(1-q(1))$ resulting in $E_P(1)$ as the specific emergy of the product given as:

$$E_P(1)=q(1)E_c(1)+E_i(1)(1-q(1))+q(1)E_i(0) \tag{2}$$

In the special case where $E_i=E_i(0)=E_i(1)$, equation (2) gives:

$$E_P(1)=q(1)E_c(1)+E_i(1) \tag{3}$$

At a time $t_2$, indicating a second recycle operation, if *q(2)* is the amount of material from the first operation to undergo recycling, $E_P(1)q(2)$ is the specific emergy it already contains. $E_c(2)q(2)$ is the additional specific emergy it needs for the current recycling operation, $E_i(2)(1-q(2))$ is the specific emergy of the new raw material to be inputted in the operation resulting in $E_P(2)$ as the emergy of the product, it gives:

$$E_P(2) = q(2)E_c(2) + E_i(2)(1-q(2)) + q(2)E_P(1) \tag{4}$$

In the special case where we have $E_i$, $E_c$ and $q$ constant, results in equation (4) as:

$$E_P(2) = E_i + qE_c + q^2E_c \tag{5}$$

In the third recycling ($t_3$), it follows from the previous derivatives. Thus the specific emergy output ($E_P$(3)) as in the special case where we have $E_i$, $E_c$ and $q$ constant is given as:

$$E_P(3) = E_i + qE_c + q^2E_c + q^3E_c \tag{6}$$

This continues for any other additional recycling. It is important to note that since there are more or less differences between each two recycling processes, due to conditions of manufacture, technological levels and material inputs, emergy input for 100% material recycling $E_c$ would definitely differ in terms of real values but remains as the notation, $E_c$, for all recycle times (1st, 2nd, 3rd, 4th …nth). As shown in the equations above, assuming that the initial emergy amount ($E_i$) remains constant in all stages of the recycle, increasing the amount recycled (*q*:i.e. a fraction between 0-1) does not cause the proportional reduction of $(E_i(t))$ in total though there is a reduction of new raw material needed for the recycle operation due to the substitution of the recycled material.

It is also worthy to mention that in emergy accounting only the flows that are crossing the system boundaries must be accounted for. As such internal generated waste where part of it is recycled to another internal system in the process is not recounted to avoid double counting. In this case only the external emergy used for the recycling is accounted for. However, where the waste generated by a system is used by another system, the flow is accounted for. With the different cases described above, a general equation could then be deduced to calculate the emergy in the product ($E_P$) at a recycle time $t$. Let us deduce this from the simplified flow diagram in fig. 4.

Fig.4. Simplified emergy flow diagram (emergy flows during recycle operation)

Then, the specific emergy balance is then written as:

$$E_P(t) = q(t)E_c(t) + E_i(t)(1 - q(t)) + q(t)E_P(t-1) \tag{7}$$

which results in the special case when $q$, $E_i$ and $E_c$ are independent of time, we have:

$E_P(1) = E_i + qE_c$ for the 1st Recycle

$E_P(2) = E_i + E_c(q + q^2)$ for the 2nd Recycle

$E_P(3) = E_i + E_c(q + q^2 + q^3)$ for the 3rd Recycle

$E_P(4) = E_i + E_c(q + q^2 + q^3 + q^4)$ for the 4th and so on.

Therefore, for $N$ number of recycles this then gives:

$$E_P(N) = E_i + E_c(q + q^2 + q^3 + q^4 + ... + ... + q^N)$$

$$= E_i + qE_c(1 - q^N)/(1 - q) \tag{8}$$

Patten (1995) discussed the effects on emergy of tracing the available energy used through multiple passages through an ecosystem network. Equations were derived based on the behaviour of the multiple passages. An exponential increase was observed, creating a cumulative flow for such continuous passages through ecosystem networks. The exact formulae are proposed here (under assumptions) based on another approach. From the discussion above, it is clear that considering or ignoring the time pathway of a recycle flow in an emergy evaluation could have enormous impact on the final results. This is even more evident when recycling is done continuously for a specific number of times. Fig. 5 shows the effect of cycle times in recycling on the specific emergy of the recycle flows.

Fig. 5. Effect of cycle times (number of times recycle) on the specific emergy of the recycle flows

It is observed that as cycle times (number of times a material undergoes recycle) increase in recycling flows, specific emergy increase which adds to the memory of the pathway. This is a continuous accumulation of specific emergy amounts as the number of times recycle is done increases. Since emergy accounts for the 'past' or the memory of a flow pathway, it is necessary to add this emergy introduced by the recycling effect at that discrete time. The scale of this discrete recycling is greater than the time taken into account for calculations of input energy involved in refining and transformation of the raw material to its final product. Especially in cases of encapsulation or system aggregation where detailed flow pathways are ignored, the evaluation could be over simplified, not accounting for this effect.

Depending on the number of times of internal feedback flows, it is then necessary to take into account a correction factor. From equation 8 above, in the special case when $q$, $E_i$, $E_c$ are independent of time, this correction factor would be, $\Psi = (q + q^2 + q^3 + q^4 + ... + ... + q^N)$, which helps to correct emergy evaluations involving a number of recycles ($N$). In most aggregated feedback systems, as shown in fig. 6, it is possible that single units within the system may have undergone certain process transformations such as re-circulation etc as already discussed.

Fig. 6. Introduction of a correction factor ($\Psi$)

Earlier on in fig. 4, it was necessary to calculate the individual emergy flows. However, in fig 6, a correction factor is introduced, i.e. $\Psi$, which makes it easier for the calculations. As a matter of fact, the important thing is to calculate $E_c$ and only multiply by the factor $\Psi$, depending on the number of times of recycle.

Fig. 7. The impact of continuous recycling in a process

Fig. 7 shows the behaviour of recycle patterns based on this factor on the number of times of recycle ($N$) and the rate of recycling ($q$). Comparing 10% and 100% recycling rates for example, the impact of this factor is not that significant for a first recycle operation. However, the significant difference is greater at higher recycle times. It is important to emphasize that; the hidden information within recycle flows in such emergy synthesis can not be ignored. At lower recycle rates, a certain asymptotic behaviour is also observed which indicates that at higher recycle rates (e.g.100% recycle rate) emergy can be defined only as a function of the number of times of recycle. One can also predict the impact between recycle times ($\varepsilon$) i.e. between $N$-$1$ and $N$ (between a current recycling and a preceding one) and determine the time step which will result in an asymptotic behaviour. As such, $f(q,N) - f(q,N-1) = \varepsilon$ gives $q^N$.

Fig. 8. Asymptotic behaviour at different recycling rates

Therefore one can determine the number of times of recycling to consider in order having a specific asymptotic behaviour. Fig. 8 shows the asymptotic behaviour at different rates of recycling. From fig. 8, it is observed that, asymptotic behaviour is more favoured at lower recycling rates.

## 4.0 Case study

The method is applied to two different groups of materials mostly used in the building and construction industry. The first comprises of metallic materials (steel, aluminium) and the second, non-metallic materials (glass and plastics).

(a) Evaluation of steel and aluminium recycling processes in the building and construction industry

Steel is among the most used and also recycled and important materials in world economy (Zhang et al, 2009) especially in the construction industry. In this particular industry, steel is easily reclaimed and reused in new building works. Reclaim of steel from demolished buildings for recycling is a common and ancient practice in the steel industry. New steel is often made in part or all from reclaimed steel scrap from different sources, reducing environmental impacts from steel production. Comparing the primary energy burden, when compared with the use of only virgin raw materials, current recycling operation of stainless steel production represents a reduction of 33%, and 100% recycling of stainless steel production would represent a reduction of 66% (Johnson et al., 2008).

Data for this case study is collected from the thesis presented by Buranakarn V. (1998) in which he studied the recycle options of some building materials. In clearly defining emergy intensity of recycling operations, he states that emergy intensity is not transformity or emergy per gram but rather reflects the energy inputs required to bring a material back to a previous stage, in which its transformity or emergy per gram is the same as a raw material input at that stage. Only the emergy required in recycling facilities is added into the evaluated processes to avoid double counting. He evaluated the recycling of steel via two recycling alternatives. He presented the options of using post consumer scrap steel as substitute for the pig iron input and also considered a combination of by product steel from the production process and post consumer scrap steel as substitute for pig iron input. In the conventional steel process which does not involve any recycle, the pig iron is the largest input comprising about 70% of the total inputs. The fuels and electricity represent about 25% of total inputs. In the first recycle process additional emergy is used in collection and separation. These inputs add slightly to the total inputs of the production process.

Table 1
Emergy evaluation table for the conventional production of steel via the electric arc furnace process (Data from Buranakarn, 1998)

As discussed above, Table 1 shows a situation of the first case, where there is no recycle operation i.e. $q$=0; $E_c$=0 and as such: $E_P(0) = E_i(0)$. Performing such an emergy evaluation with an annual base period (i.e. per year) requires no additional time for recycling (i.e. $t_0$). In this case, the sum of the total emergy inputs (pig iron, natural gas, other fuels etc) based on their respective annual (yearly) quantities ($Q$) as evaluated, gives the emergy of the product i.e. 1.86E+23sej/yr and a transformity of 4.15E+09sej/g.

Table 2
Emergy evaluation table involving recycle of post-consumer steel via the electric arc furnace process (Data from Buranakarn, 1998)

In Table 2, Buranakarn (1998) has taken into account the same labor for each raw material whatever the cycle (conventional or recycling). This assumption could be usefully revisited in a dedicated work, as indicated by an anonymous reviewer.

The main difference between the two tables presented, is the additional emergy needed for post consumer steel collection and separation for the recycle process (Table 2). This represents the additional emergy needed for the collection of used steel from landfills and other sources and the corresponding additional emergy needed for sorting or separation. This is represented by item 3 and 4 on Table 2 with transformities of 2.51E+8 and 8.24E+6 respectively. As such, Table 2 presents the system involving recycling.

It is considered that the 70% new raw material input represents 0.7$E_i$. In this specific case, q, which is the rate of recycling, is given as 30%. As such, from equation 3, which was earlier on mentioned, $E_P(1) = E_i + qE_c$, where $E_i$ is the emergy of the total inputs without recycle and equals $E_P$ in that specific case. As such, the emergy contained in the material to be recycled is $E_P$ where $E_P = E_i$ in the specific case, $E_i$ = 1, 86E+23 seJ. From the data (see Buranakarn, 1998 p52), the emergy needed for collection and separation for a 100% material recycle is 1.13E+23 seJ and 3.70E+20 seJ respectively.

Applying equation 3, then gives: $\left(1.86x10^{23}\right)+0.3\left(3.7x10^{20}+1.13x10^{23}\right)\approx 1.90E+23sej/yr$

However, this could also be done by the method explained in the previous sections. Therefore, calculating $E_c$ and $\psi$, $E_P$ could be calculated. Figure 9 presents the evaluated emergy results for different recycle times for recycling rates of 30% and 90%.

Fig. 9: Continuous recycling of steel based on 30% and 90% recycling rate.

It is observed that at both 30% and 90% recycle of steel scrap, there is a gradual accumulation of emergy from the first, second, third recycle and so on. In the third recycling, for example, it is seen that the material ($q$) undergoing recycling has already been subjected to a first ($1$-$q$), second $(q(1-q))$ and now a third ($q^2$) recycling. As such this accumulative effect must be considered in the final emergy output of the system. Note, that this is not double counting as already explained. The correction factors achieved was again extended to calculate for aluminium sheet recycle. Table 3 gives the emergy results for the conventional process and Fig. 10 shows the behavior if the recycle continues for a number of times for different recycle rates (q=30% and 90%).

Table 3: Results of emergy evaluation of conventional aluminium production and recycling of used aluminium cans

Fig. 10: Continuous recycling of used aluminium cans for 30% and 90% of material recycle

(b) Emergy evaluation of plastic and glass (ceramic tile) recycling

This could be applied to several other material recycling options to evaluate the different impacts. Data for the emergy evaluation of plastics and glass (ceramic tile) were collected from an emergy synthesis study presented also by Buranakarn (1998). In both recycle processes, there are associated costs of collection and sorting and as such the emergy per mass of the product from the recycle processes are higher than the conventional process (Tables 4 and 5). In Table 4, the emergy evaluation of conventional plastic lumber production is given with that of a recycling process; assuming that post consumer plastic (e.g. milk bottles) and paper are substituted for the plastic resin and wood fiber. These are associated with costs of collection and sorting and as such, the emergy per mass reuse of post consumer plastic results in an emergy per mass of 6.33E+9 seJ/g.

Table 4: Emergy evaluation of conventional and recycle process of plastic lumber (data from Buranakarn (1998))

Table 5: Emergy evaluation of conventional and recycle process of glass (data from Buranakarn (1998))

Figure 11 shows the pattern of results obtained for the product emergy values ($E_{P_{\text{glass}}}$, $E_{P_{\text{plastic}}}$) when the correction factor is used in calculating these values for their respective recycle times and rates.

Fig. 11: Continuous recycling of post consumer glass (ceramic tile) and plastic for both 30% and 90% recycle

The general principle is the same for each material, for example, the recycle of a material is much affected by the recycling rate (q) and the number of times the recycle is done. Criteria to judge appropriate optimum levels for both recycle times and rates depends on the asymptotic behaviour of the respective patterns for the recycle operation. The output emergy values from the continuous recycling tables presented, further helps to emphasize the accumulation effect of continuous recycling at different increasing rates during material recycling. It shows the gradual increase of specific emergy amounts between the first, second, third, etc recycle times. This is important to be accounted for during an emergy evaluation.

## 5.0 Discussion

This work seems to break the link between eMergy and exergy of a product. First question relates to: is it a pure mathematical paradox in the rules of eMergy? Is it consistent with previous work? What were the previous solutions to avoid the cumulative problem in a reuse? What are the consequences?

### 5.1 Mathematical paradox?

In many studies (Bastianoni et al., 2002; Meillaud et al., 2005; Odum, 2000), emergy is calculated as the product of energy (over a specific period) and its associated transformity (often selected from a reference database). However, in this paper this strong relation seems broken. This paper suggests that an increase in the emergy of a product does not necessarily correspond to a change in the exergy (useful available energy) in the product.

It is important to recall that emergy is a 'cumulative' measure and again does not take into account the (time) depreciation. There are quite a few published papers which demonstrate the time dependence in the emergy concept (Odum and Peterson, 1996; Tilley and Brown, 2006). In respect to the approach presented by the authors in this paper, one can argue that a similar product could have different transformities just because one has a portion of recycled material in its production. However, authors are of the view that since transformity = emergy (input)/ exergy, emergy (input) can increase without a change in exergy. From the first law of thermodynamics:

$$dU = \delta W_{ext} + \delta Q \quad \text{or} \quad m\,du + u\,dm = \delta W + \delta Q \tag{9}$$

where $U$ is internal energy, $W$ external work and $Q$ received heat.

Consider a product (water in a tank, for example in steady state: no input or output flow in which continuous electric power (input of emergy flow) balances heat losses to the environment) under (time) depreciation with its environment (heat losses for example). If one wants that this product keeps the same useful available energy, one has to add external energy (in a case of heat losses ($\delta Q_{loss} = hS\Delta T$)). Assuming that $\delta W = 0$, if one wants that the temperature $T$ is constant, then one has to add energy (by electric converter, for example) $Q_{add}^{elec} = -Q_{loss}$ which gives:

$$dU = \delta Q_{add}^{elec} + \delta Q_{loss} = 0 \tag{10}$$

Odum (1996) stated the first rule of emergy calculations as: "all sources of emergy to a process are assigned to the processes output." As such $Q_{add}$ must be taken into account for emergy value. In other words, if a product is under (time) depreciation, to keep the same useful available work we have a "cost" to pay to Nature (as "CARNOT formula" but in this case $dEx = \left(1 - \frac{T_0}{T}\right) C_v \; dT = 0$ (e.g. Dincer and Rosen, 2007, pp17-19) for the water in the tank). In our view, use of a product under (time) depreciation (for example the mass losses for the "new production") does not really damage its useful available "value" but require additional energy to recover the same useful available "value" (as a cost to pay to Nature). The formulae recounted in this paper contain the same behaviour.

## 5.2 Consistency

Considering the work of Buranakarn (1998, pp 53-58) for example, pig iron (100%) transformity = 4.15E+9seJ per gram whilst for post consumer steel scrap, transformity = 4.41E+9 seJ per gram. For 70% steel scrap and 30% post consumer steel, transformity = 4.24E+9 seJ per gram. In this example, authors demonstrate a way of accounting for the emergy of a material which is reused without necessarily violating any of the emergy rules. This goes to show that transformity is a function of the pathway: 4.15E+9 (0% recycling) versus 4.41E+9 (100% recycling) seJ per gram. The formulae recounted in this paper give exactly the same results.

## 5.3 Consequence

Two major consequences are highlighted.

The first one concerns the calculations. As a result, in this paper, as in the case of several papers (e.g. Odum, 2000 pp 389-393) where emergy tables are employed, it would be necessary to create an additional column. Actual table for eMergy evaluation is mainly composed of 4 columns: {*Item*; *Data unit*; *Solar emergy/unit*; *Solar emergy*}. For an *Item* with its own previous time pathway, authors suggest a sub-composition of the third column {*Solar emergy/unit (pure)*; *Solar emergy/unit (its own time pathway)*} and e.g. for recycling {*Solar emergy/unit (raw)*; *Solar emergy/unit (additional eMergy)*; *correction factor* $\psi$ }.

The second one concerns the analysis. In order to reuse or recycle waste material that still has a potential to be used, an emergy investment is needed. As already mentioned in the introduction, Ulgiati et al. (2004) points out that for an emergy evaluation to be reliable, the emergy input required for waste treatment, safe disposal, or recycling must be accounted for. Undertaking an emergy evaluation on such a system therefore means in principle that the transformity of the recycled material should be calculated accounting for both the investment for recycling and previous input to the process that generated the waste. However, evaluating a system in this manner would be double counting if one needs to assign to it the whole emergy it bore when it was still in the finished product form. Ulgiati et al. (2004) then proposes a path of emergy allocation in order not to violate the emergy rules in which only the emergy invested in the treatment and recycling process should be assigned to the recycled resource. As such, the proposal suggests that wastes only bear the additional emergy inputs needed for their further processing. Though this is a rather smart way of solving such a problem, it might lead to over simplifying a system which leads to non-accounting of the past path way of the recycled material.

Ulgiati et al. (2004) have then amounted to 'reseting' the emergy content in recycling processes to eliminate the problem of cumulative emergy. They maintain a strong link between "effective available energy" and "emergy" but the cost is a broken of emergy rules as they pointed out themselves. Consequently, without providing a "reset block" (dimensionless number) that could cancel the previous emergy of the recycled material, the difference between 4.15E+9 and 4.41E+9 seJ per gram as in the example of Buranakarn (1998) is explained by the time pathway. The idea presented in Ulgiati et al. (2004), is an alternative when no information concerning the number of recycling is available. Other alternatives are Brown's proposition (Brown & Buranakarn, 2003) keeping the value for a single recycling or keeping the maximum value which is to say the asymptotic behaviour.

## 5.4 Emergy indices

Emergy indices have been defined by Brown and Ulgiati (1997), e.g. Environmental Yield Ratio (*EYR* = total emergy divided by the non-renewable external contributions). In the referred work (Buranakarn, 1998), several additional indices were developed to evaluate the appropriateness of the different recycle systems. The Recycle Benefit Ratio (RBR) is the ratio of the emergy required to provide a material from raw resources over the emergy required to recycle a post-consumer product that is substituted for the raw resource. It provides information relative to the potential savings that can result if a material is recycled and substituted for a raw resource. The Recycle Yield Ratio (RYR) for instance is the ratio of the emergy in a recycled material to emergy used for recycle. This evaluates the net benefit that society receives for recycling. It is a measure of what society receives in emergy for its emergy investment in recycle. The RYR is similar in concept to the Emergy Yield Ratio (EYR) used to express the net benefits to society from energy sources (Brown and Ulgiati, 1997).

This paper does not seek to propose a change in the use of these indices but rather proposes new indices to analyse results, just like the existing indices.

Let us denote $E_i$ as the "initial" solar emergy/unit, e.g. for raw material, $E_p$ the "preparation" solar emergy/unit $E_p=E_{extraction} + E_{transformation}$, and $E_c$ the "additional" solar emergy/unit $E_c = E_{reuse}$. Let us distinguish the renewable part and the non renewable part: subscripts 1 and 2 refer to non renewable and renewable parts respectively. With this notation, one would have: $E_p=E_{p,1}+E_{p,2}$ and $E_c=E_{c,1}+E_{c,2}$. Indices, as an extension to *EYR*, can be defined as:

$$EYR_i = \frac{(E_i + E_P)}{E_{P_1}} \tag{11}$$

Eq. 11 demonstrates the case of Buranakarn (1998); Brown and Buranakarn (2003).

$$EYR_c = \frac{E_c}{E_{c_1}} \tag{12}$$

Eq. 12 is as used and interpreted by Brown and Ulgiati (1997).

$$EYR_g = \frac{(E_i + E_P + \psi E_c)}{(E_{P_1} + \psi E_{c_2})} \tag{13}$$

Eq. 13 traces the pathway of the material as proposed in this paper.

As a matter of fact, NRR, ELR and EIR, (Brown and Ulgiati, 1997) can be extended too. The most important is to calculate these new indices to compare different systems.

Fig. 12. Impact of plastic recycle on EYR

Fig. 12 presents a typical range of values for EYRs of plastic. The different EYRs explained above ($EYR_i$, $EYR_c$, $EYR_g$) have been plotted. It shows clear differences based on the approach for calculating the ratios. $EYR_i$ is the calculated ratio without considering the impact of a recycled material and remains constant for all loops. $EYR_c$ is calculated only based on the additional emergy required for the recycle process (in this example, 25% of Ec is assumed to be from non renewable sources) and remains constant as well. However, the extended emergy ratio proposed in this paper ($EYR_g$) shows significant differences in EYRs based on the quantity of material recycled and the number of times of recycle. A steady decline of EYR is observed in all cases of N which is largely due to the additional emergy required in the recycle operation. In such scenarios where a material might have undergone several loops of recycling the emergy ratio is defined within a  range than having a specific value.

## 6.0 Conclusions

Authors have studied recycling at discrete times and proposed a set of dynamic equations to evaluate such systems involving recycling. This approach aims to contribute to the emergy evaluation of recycling processes. Since emergy researchers often adopt classical emergy indices such as EYR, EIR, ELR ESI etc., to evaluate solid wastes recycling value (Feng et al., 2007; Lou, 2004; Yang et al., 2003), consequently, additional efforts to complement the calculation procedure to reflect a rather clearer picture of these indices for recycling have been proposed with their impacts examined. Through this analogy, this paper presents a way by which emergy information loss (internal 'memory') which is generated as a result of continuous recycle operations can be accounted for in emergy evaluations. The results show significant loss of emergy history when recycling is done severally and not accounted for in emergy evaluations. Buranakarn (1998) and Brown & Buranakarn (2003) share in the view that emergy of a product increases with use of a recycled material. As a result, a recycling process would increase the emergy content of a product only once (whatever the time pathway), which is the significant point in this paper.

The concept has been applied to examples of both metallic and non-metallic materials often used in the building and construction industry. This could be extended to evaluate other material recycling processes and options. A correction factor is proposed which would contribute to a comprehensive emergy evaluation of systems with recycle.

It is obvious that traditional economics based on money is not sufficient to fully evaluate waste recycling value. As such, the emergy theory presents a rather more rewarding path for the future. The contribution of this work will add to the maximum use of the emergy theory, especially in systems with recycling.

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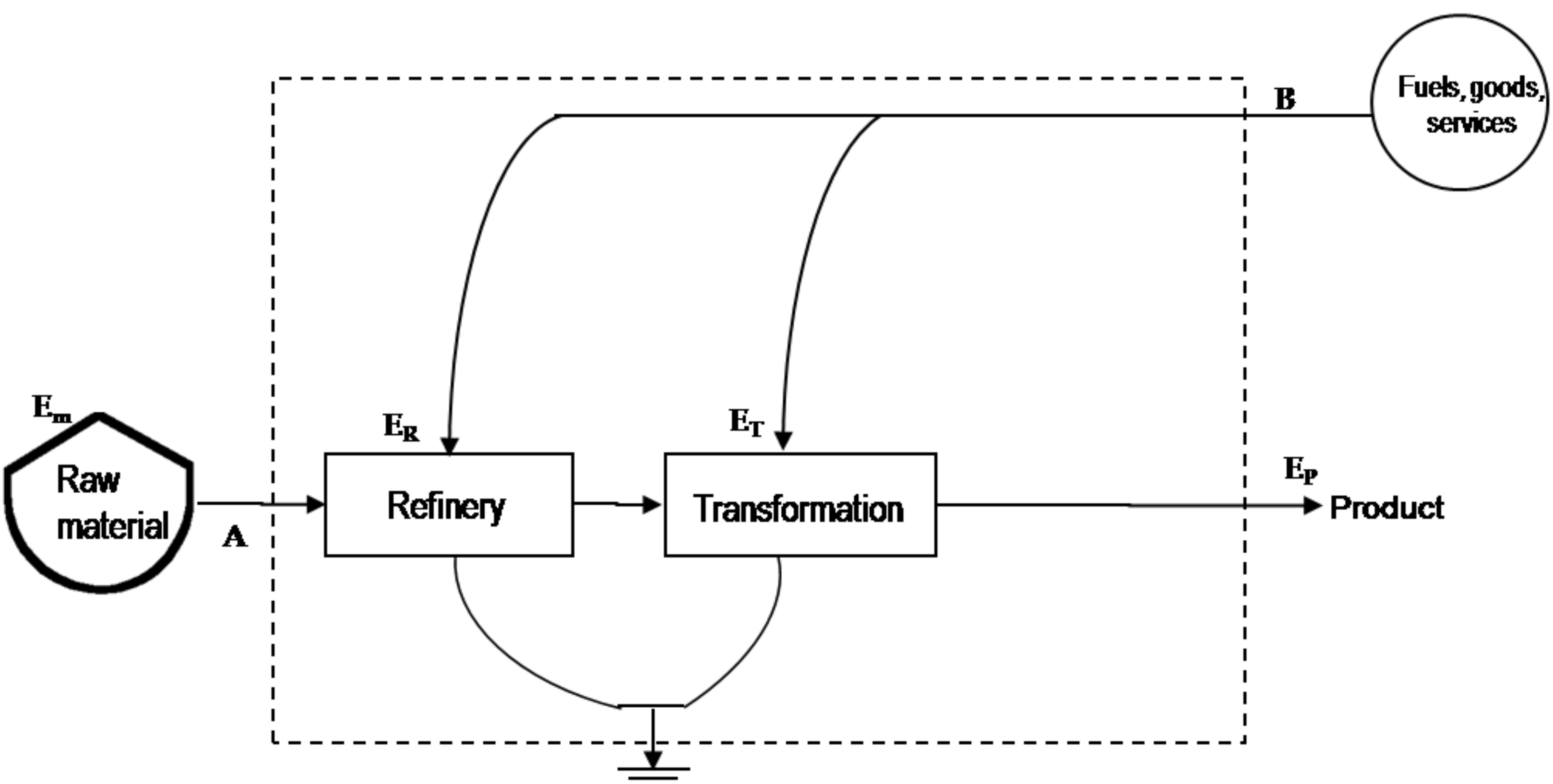
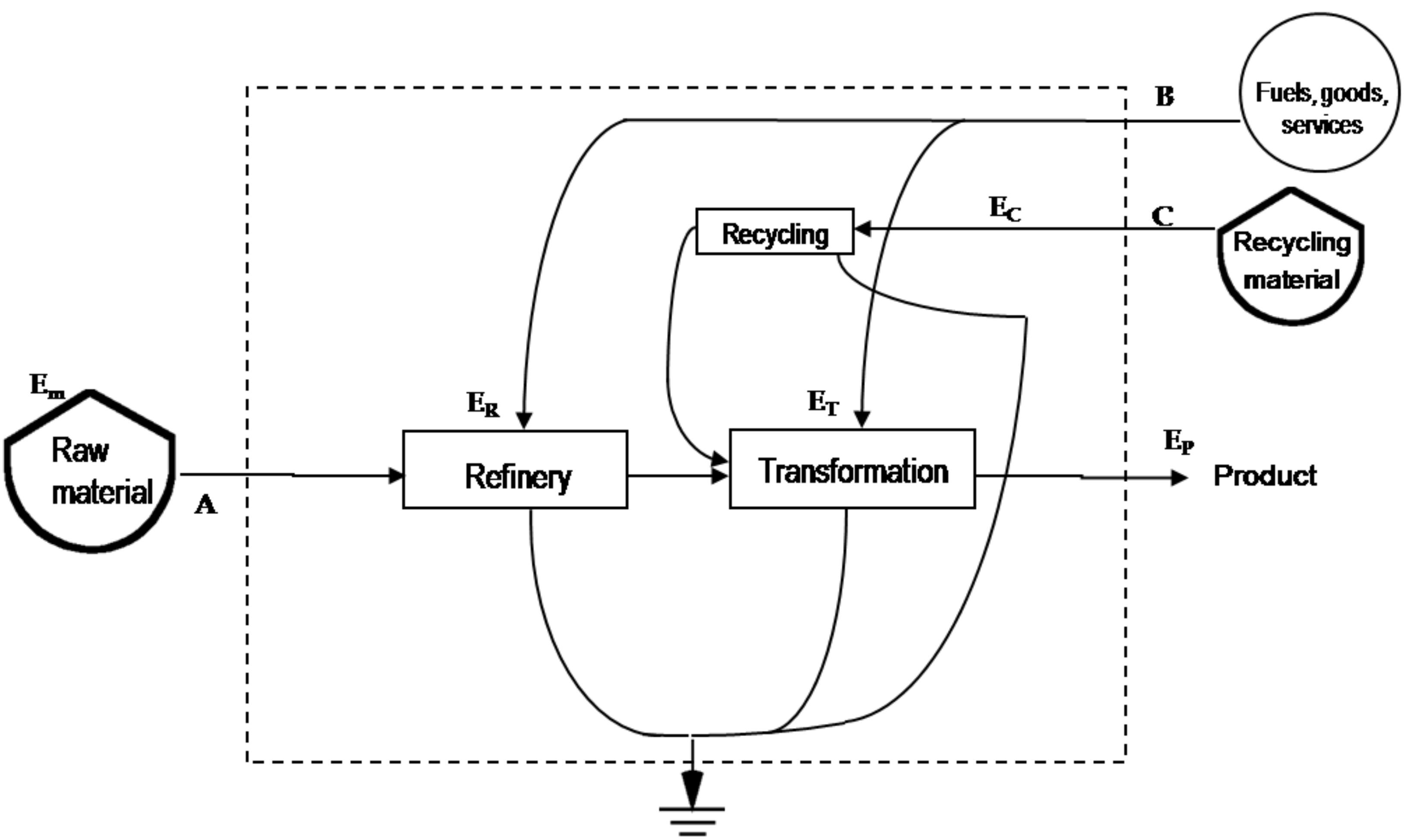
Figure 1



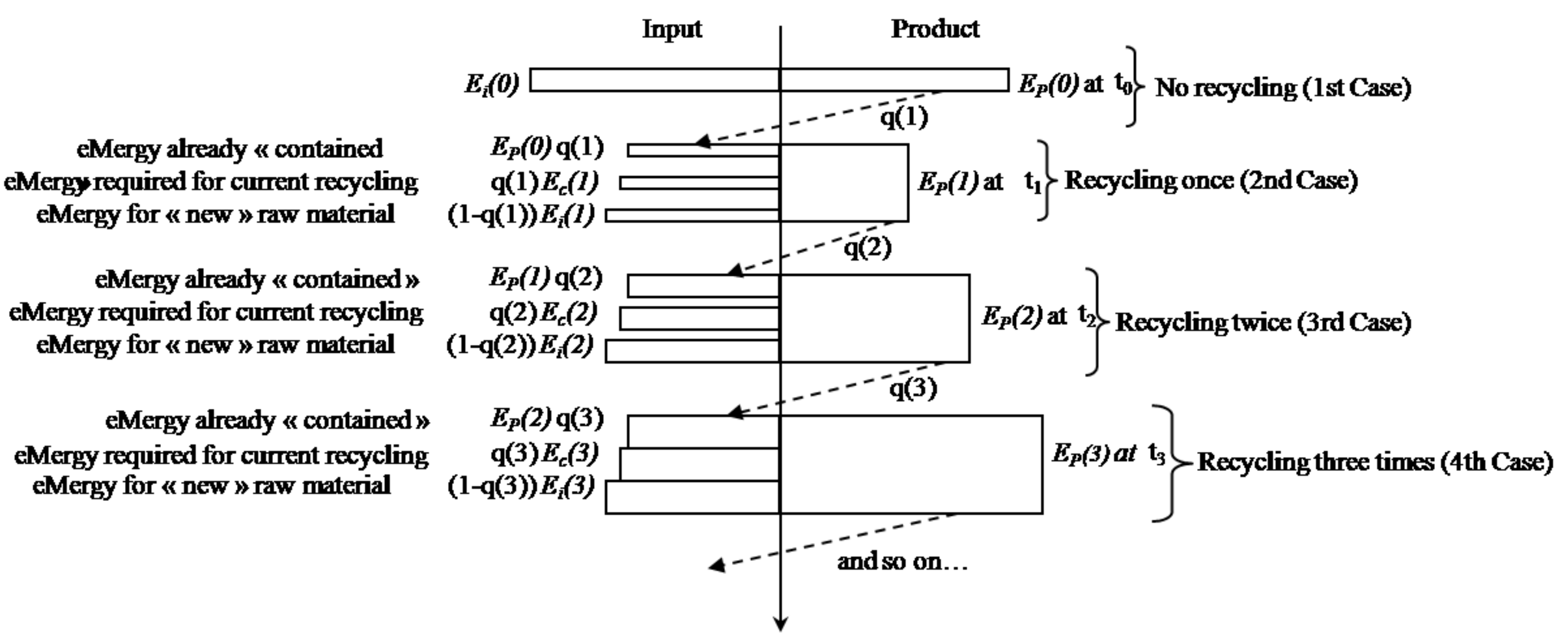
Fuels, goods, services
B
$E_m$
Raw material
A
$E_R$
Refinery
$E_T$
Transformation
$E_P$
Product

Figure 2



Fuels, goods, services
B
Recycling
E_C
C
Recycling material
E_m
Raw material
A
E_R
Refinery
E_T
Transformation
E_P
Product

Figure 3



Input
Product
Ei(0)
EP(0) at t0
No recycling (1st Case)
q(1)
eMergy already « contained
eMergy required for current recycling
eMergy for « new » raw material
EP(0) q(1)
q(1) Ec(1)
(1-q(1)) Ei(1)
EP(1) at t1
Recycling once (2nd Case)
q(2)
eMergy already « contained »
eMergy required for current recycling
eMergy for « new » raw material
EP(1) q(2)
q(2) Ec(2)
(1-q(2)) Ei(2)
EP(2) at t2
Recycling twice (3rd Case)
q(3)
eMergy already « contained »
eMergy required for current recycling
eMergy for « new » raw material
EP(2) q(3)
q(3) Ec(3)
(1-q(3)) Ei(3)
EP(3) at t3
Recycling three times (4th Case)
and so on…

Figure 4

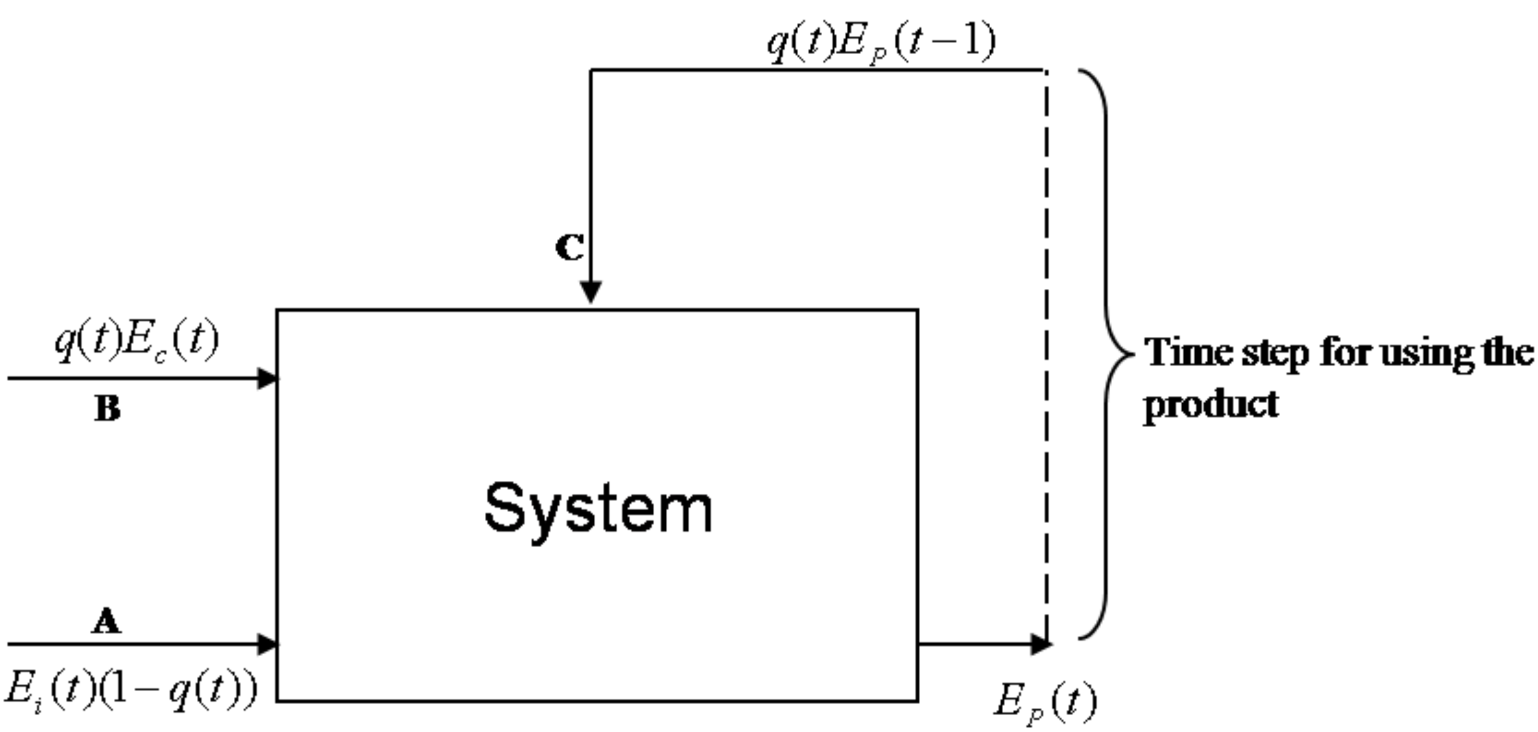
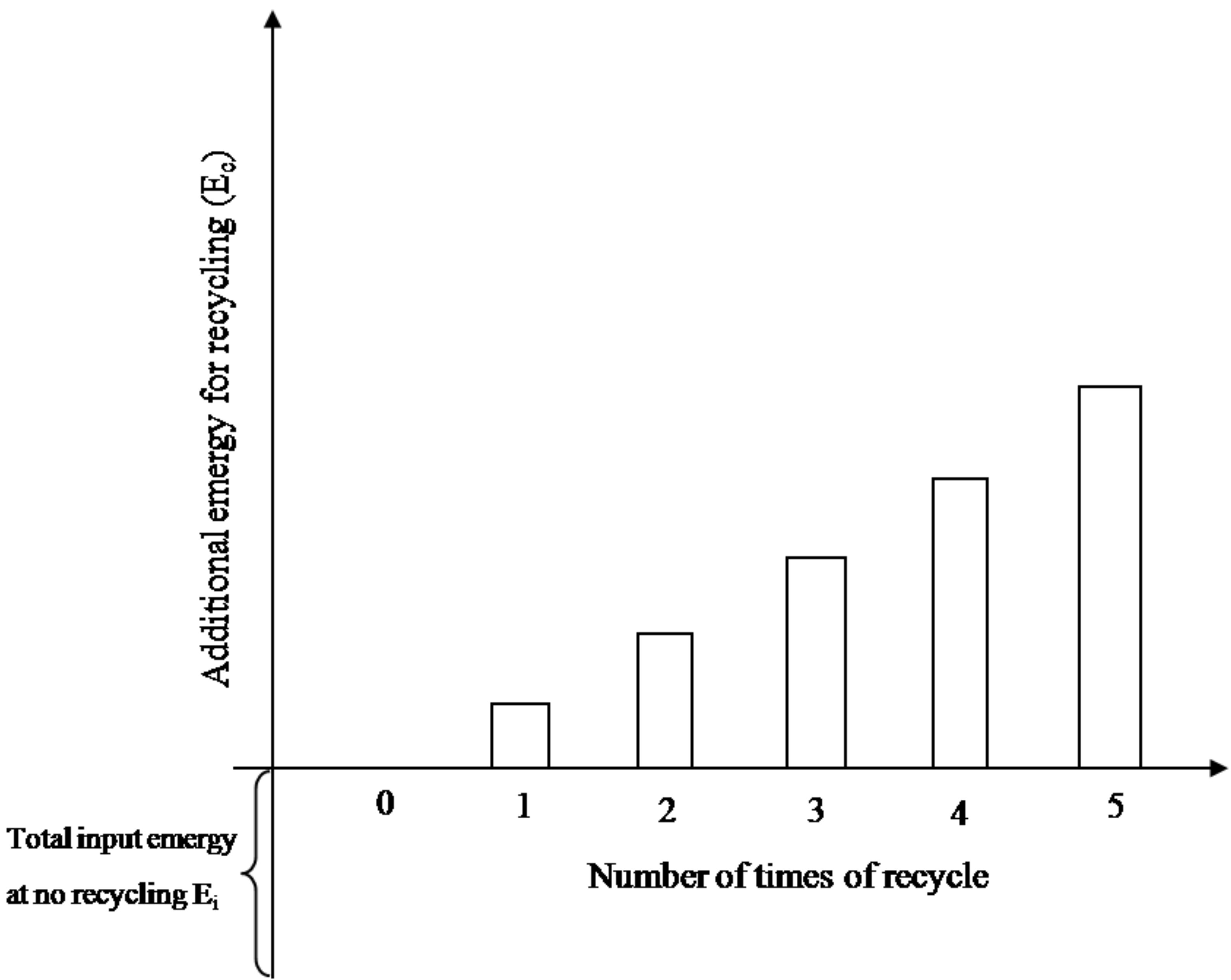

$q(t)E_p(t-1)$
C
$q(t)E_c(t)$
B
System
Time step for using the product
A
$E_i(t)(1-q(t))$
$E_p(t)$

Figure 5



Additional emergy for recycling ($E_c$)
0
1
2
3
4
5
Number of times of recycle
Total input emergy
at no recycling $E_i$

Figure 6

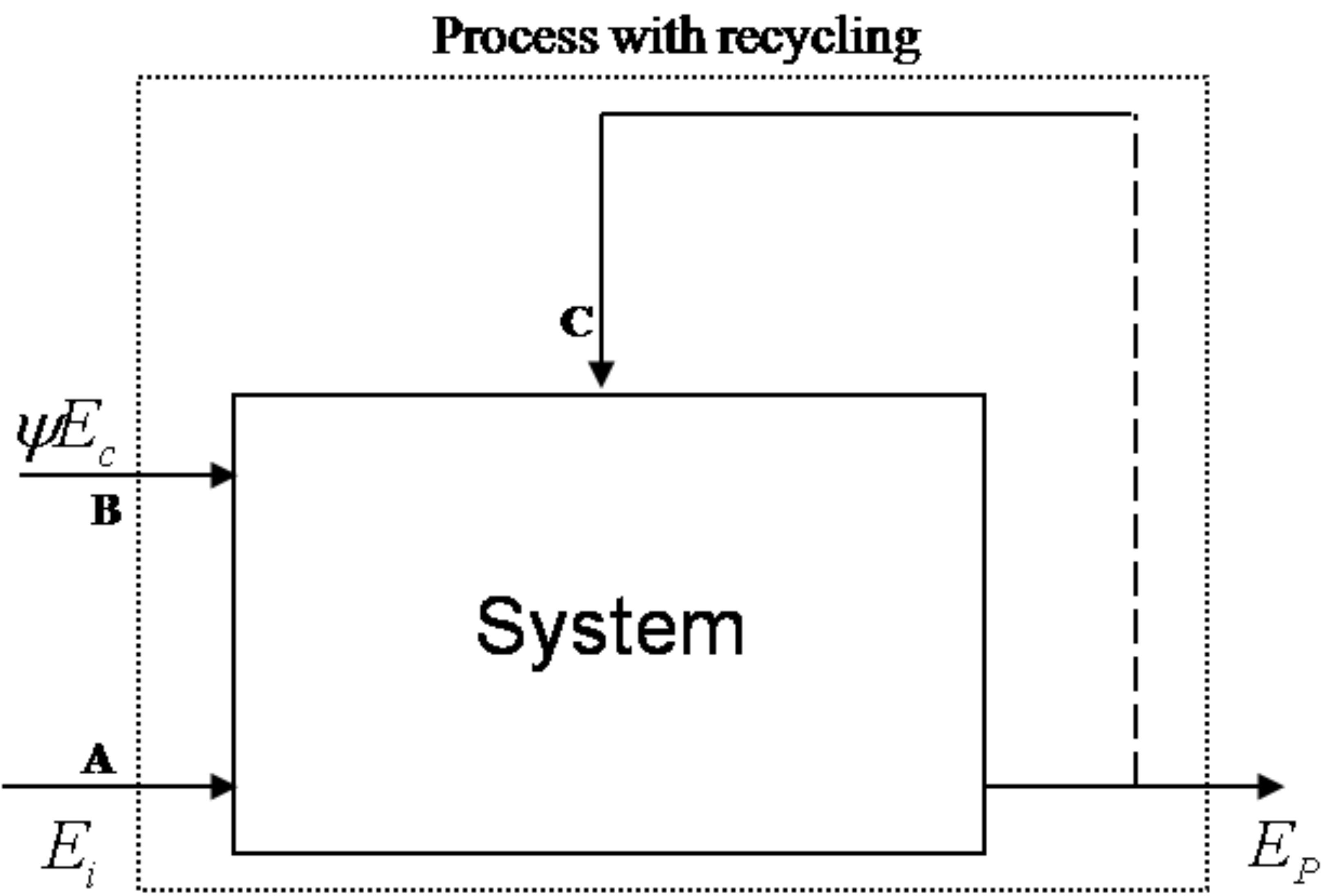
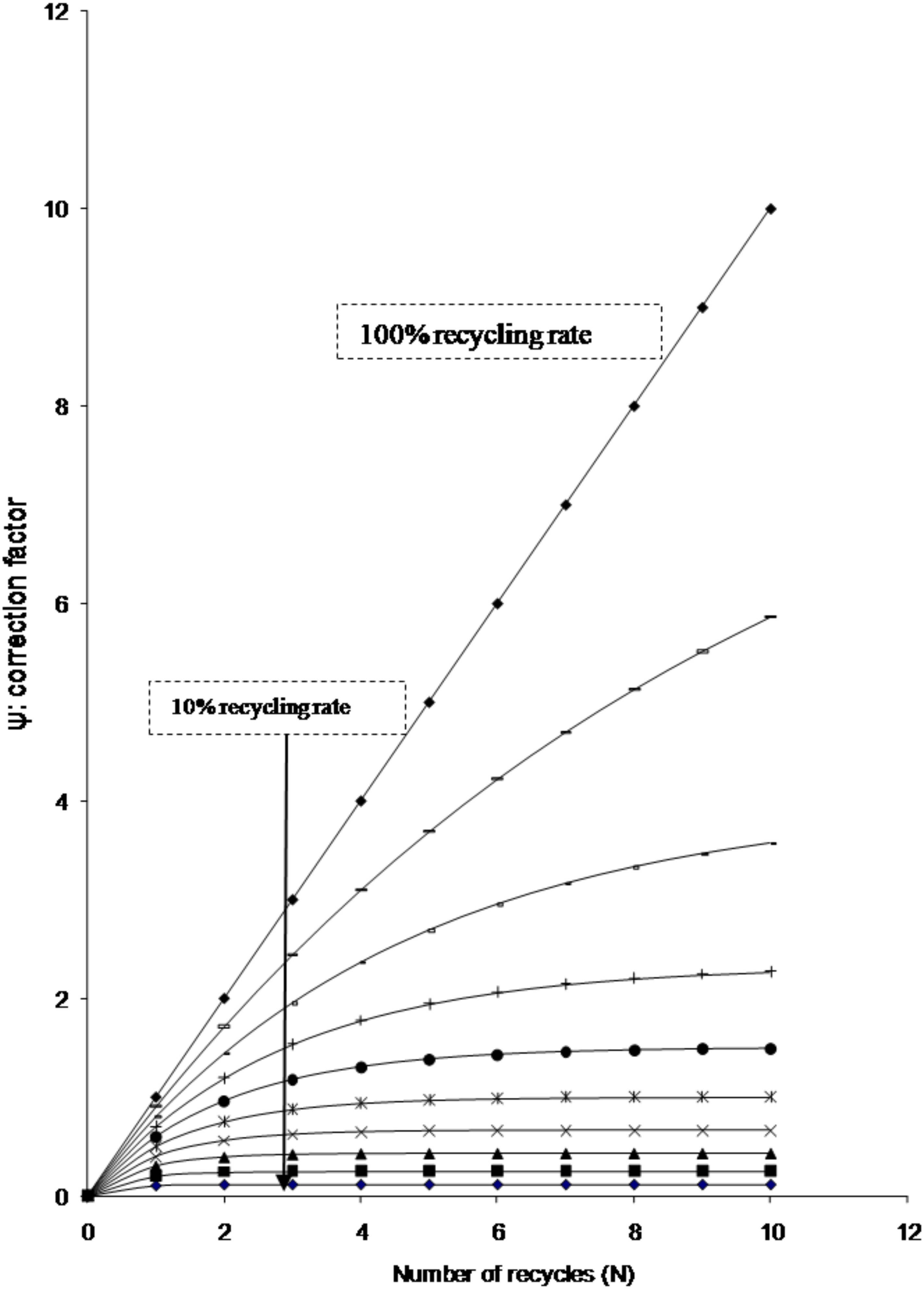
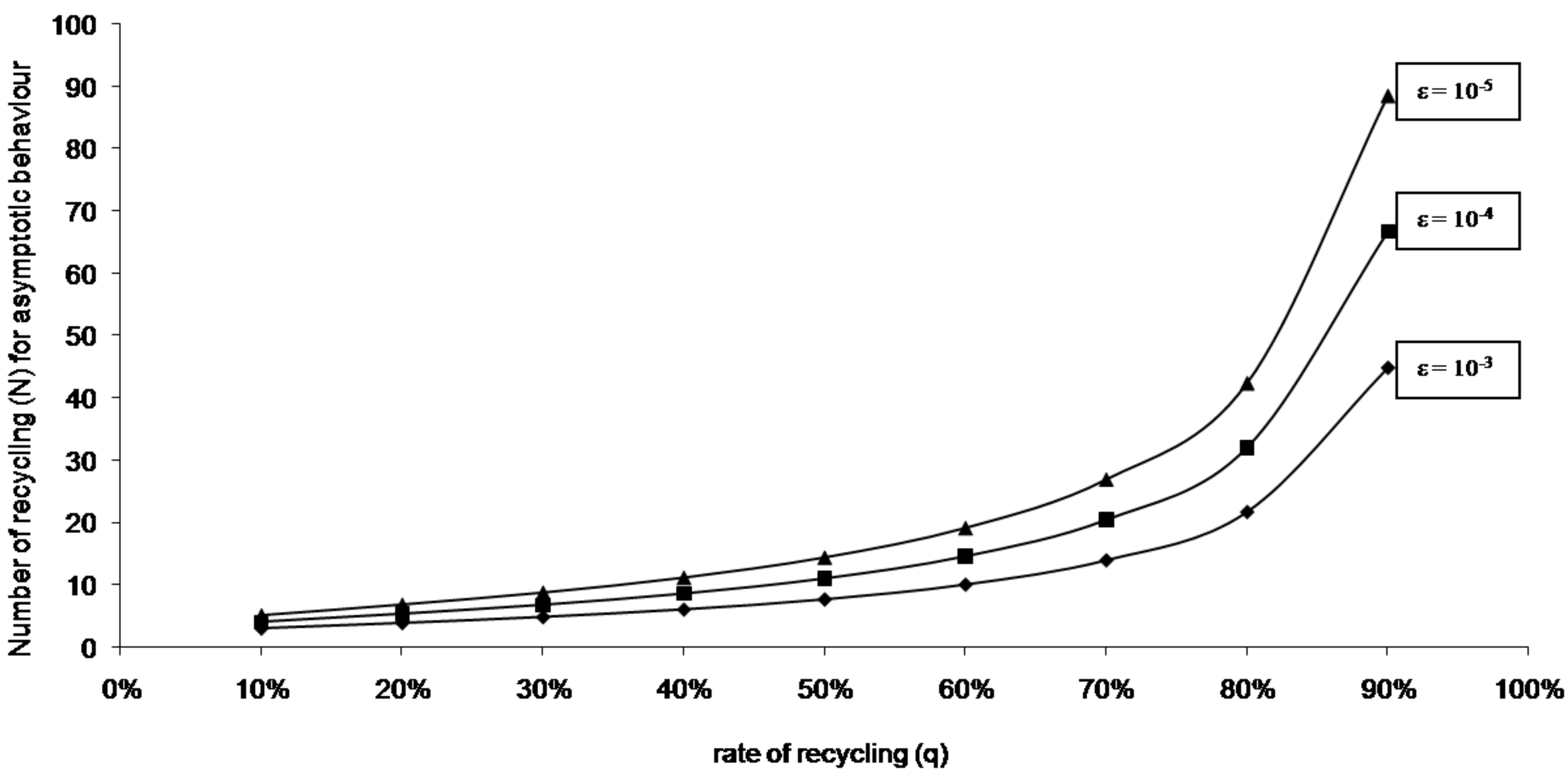


Figure 7



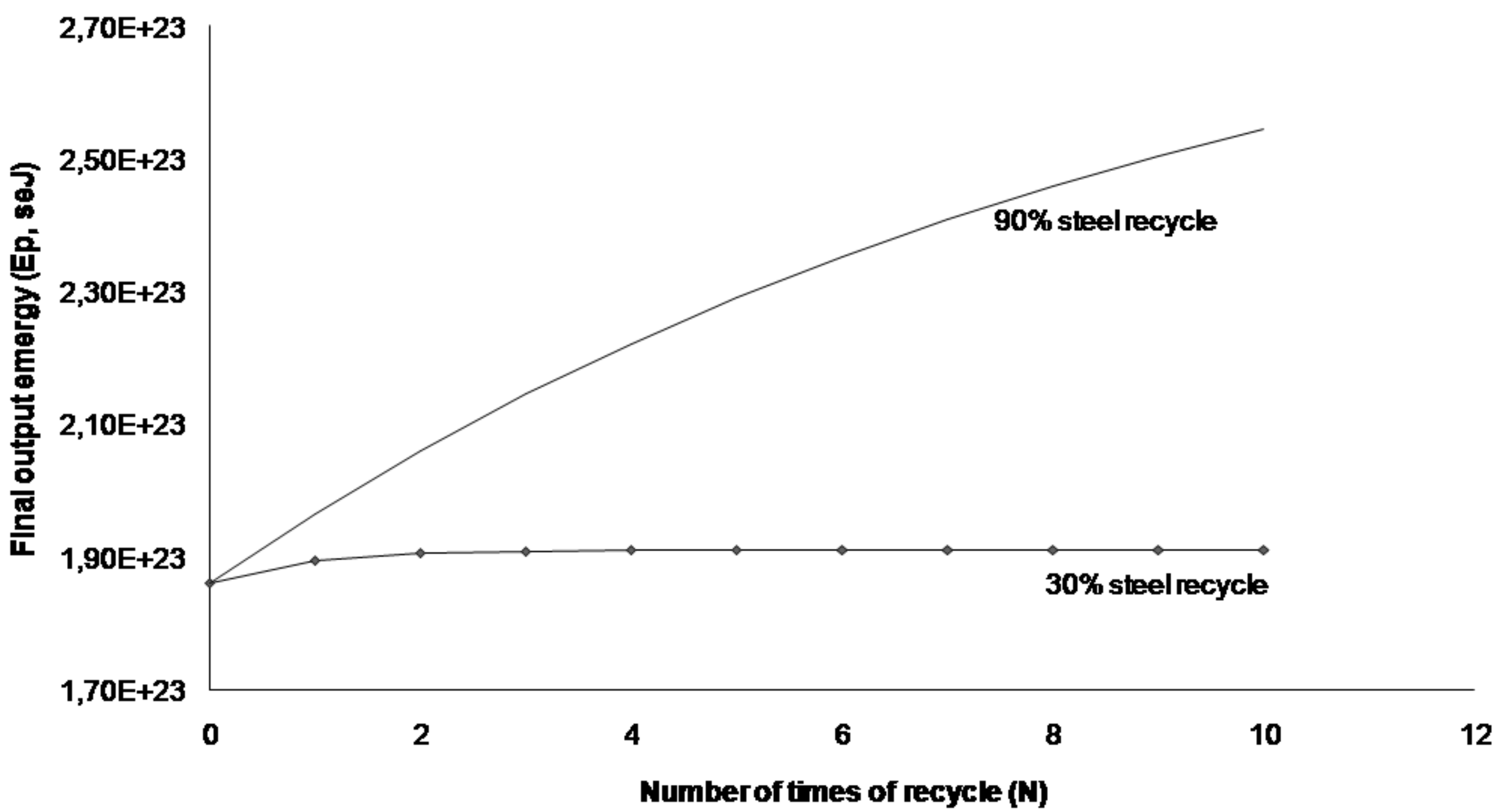
100% recycling rate
10% recycling rate
ψ: correction factor
Number of recycles (N)
0
2
4
6
8
10
12

Figure 8



100
90
80
70
60
50
40
30
20
10
0
Number of recycling (N) for asymptotic behaviour
0%
10%
20%
30%
40%
50%
60%
70%
80%
90%
100%
rate of recycling (q)
ε = 10-5
ε = 10-4
ε = 10-3

Figure 9



2,70E+23
2,50E+23
2,30E+23
2,10E+23
1,90E+23
1,70E+23
Final output emergy (Ep, seJ)
90% steel recycle
30% steel recycle
0
2
4
6
8
10
12
Number of times of recycle (N)

**Figure 10**

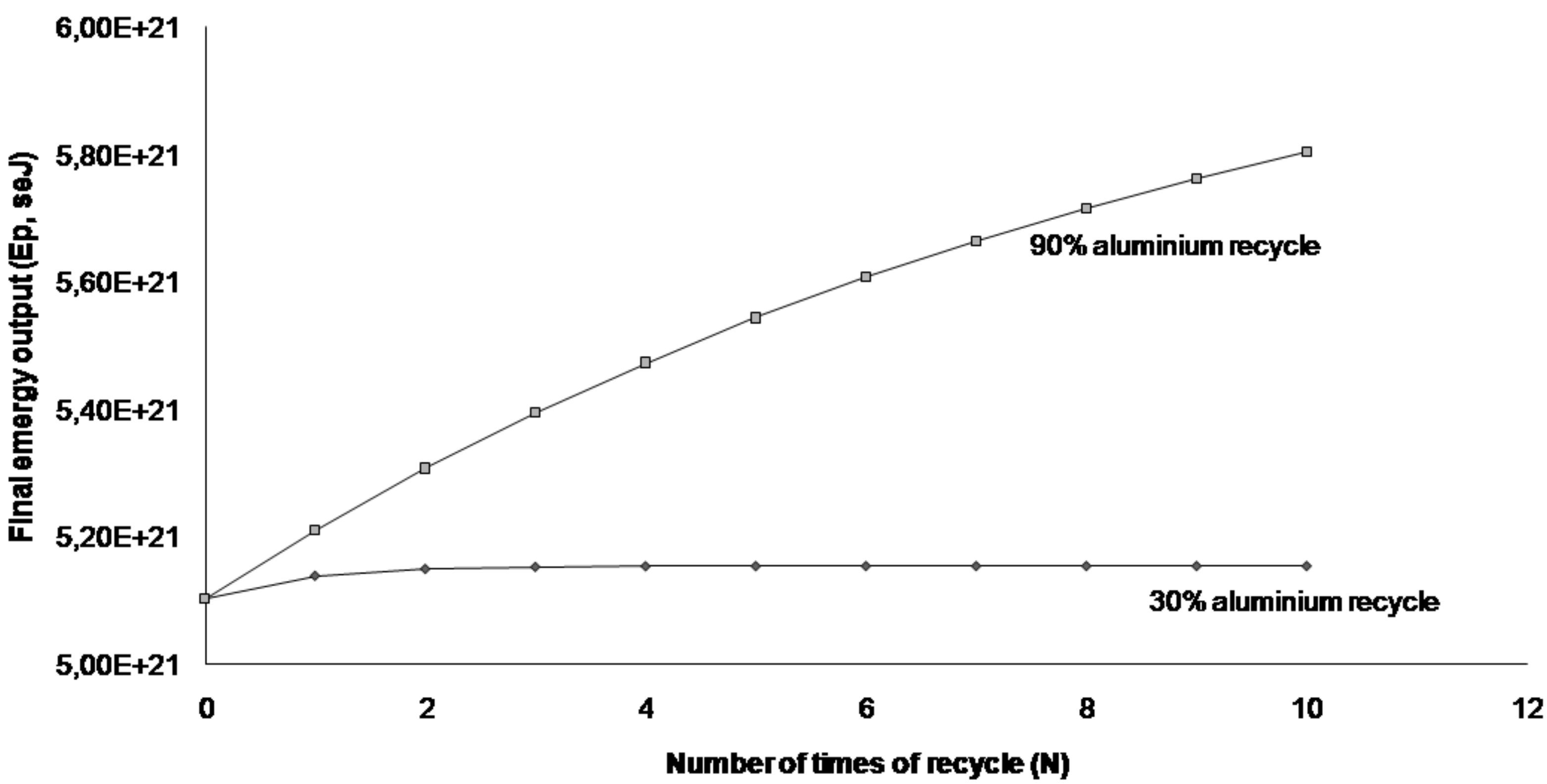
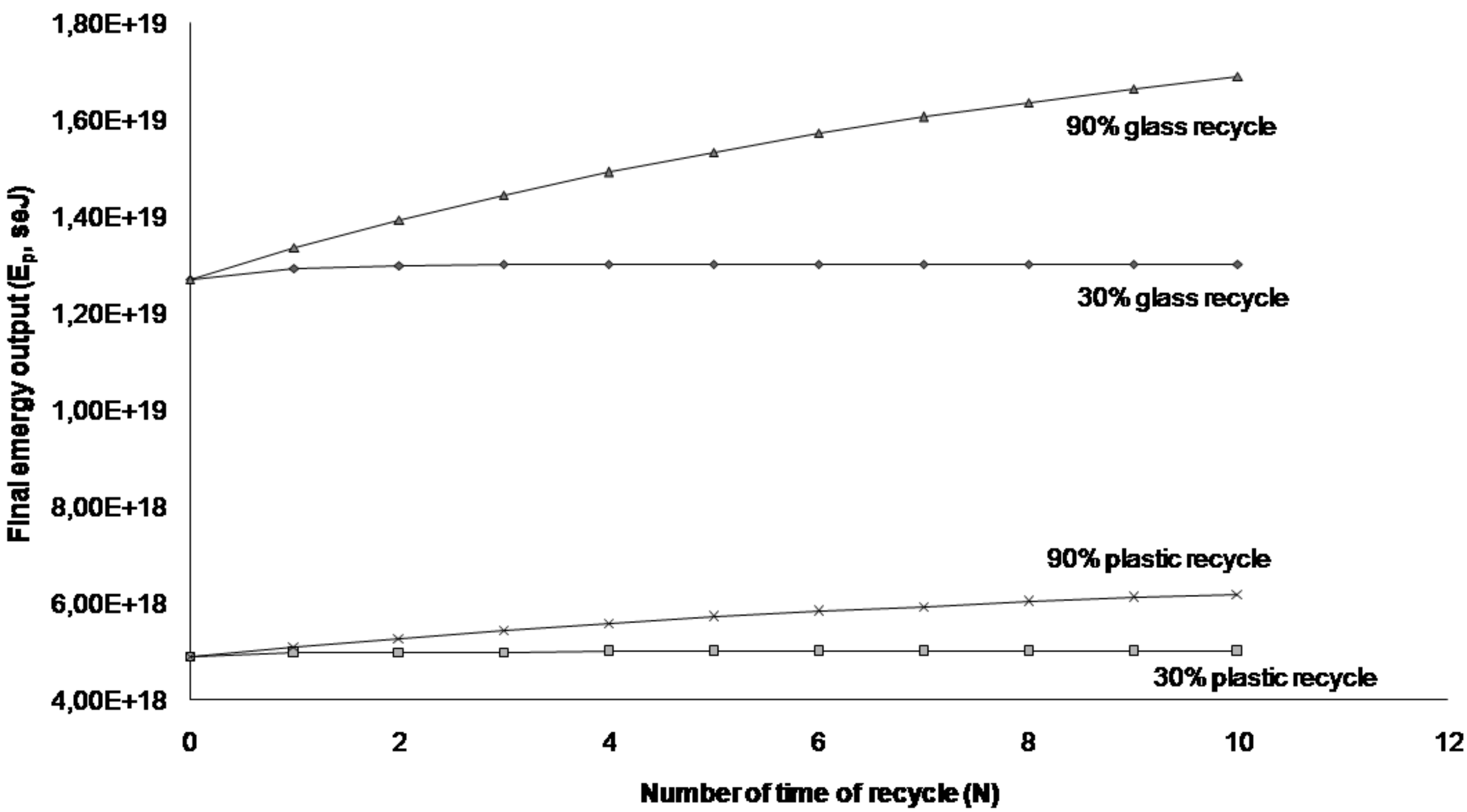
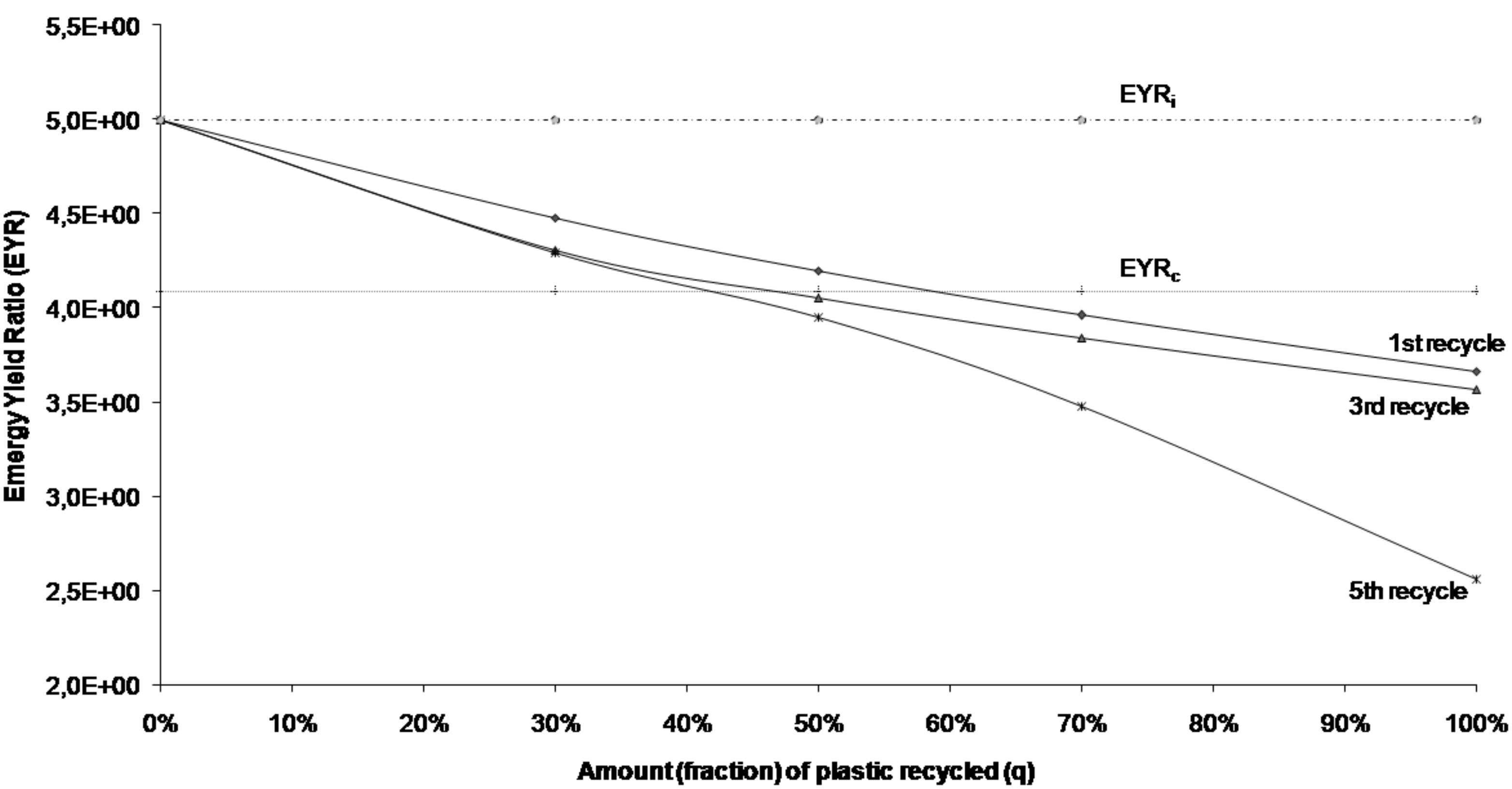

6,00E+21
5,80E+21
5,60E+21
5,40E+21
5,20E+21
5,00E+21
Final emergy output (Ep, seJ)
90% aluminium recycle
30% aluminium recycle
0
2
4
6
8
10
12
Number of times of recycle (N)

Figure 11



1,80E+19
1,60E+19
1,40E+19
1,20E+19
1,00E+19
8,00E+18
6,00E+18
4,00E+18
Final emergy output ($E_p$, seJ)
90% glass recycle
30% glass recycle
90% plastic recycle
30% plastic recycle
0
2
4
6
8
10
12
Number of time of recycle (N)

**Figure 12**



5,5E+00
5,0E+00
4,5E+00
4,0E+00
3,5E+00
3,0E+00
2,5E+00
2,0E+00
Emergy Yield Ratio (EYR)
$EYR_i$
$EYR_c$
1st recycle
3rd recycle
5th recycle
0%
10%
20%
30%
40%
50%
60%
70%
80%
90%
100%
Amount (fraction) of plastic recycled (q)

**Tables**

| | Note Item | Unit/year | Input Resource | Solar emergy per unit (sej/unit) | Emergy (sej/year) |
|---|---|---|---|---|---|
| | Conventional steel product | | | | |
| 1 | Pig iron | g | 4,53E+13 | 2,83E+09 | 1,28E+23 |
| 2 | Natural gas | J | 3,17E+17 | 4,80E+04 | 1,52E+22 |
| 3 | Other fuels | J | 2,80E+16 | 6,60E+04 | 1,85E+21 |
| 4 | Electricity | J | 1,84E+17 | 1,74E+05 | 3,20E+22 |
| 5 | Transportation | ton-mile | 7,50E+09 | 9,65E+11 | 7,24E+21 |
| 6 | Labour | $ | 1,58E+09 | 1,20E+12 | 1,90E+21 |
| 7 | Annual Yield | g | 4,49E+13 | 4,15E+09 | 1,86E+23 |

**Table 2**

| | Note Item | Unit/year | Input Resource | Solar emergy per unit (sej/unit) | Emergy (sej/year) |
|---|---|---|---|---|---|
| | Material recycling and byproduct use steel product | | | | |
| 1 | Post consumer steels | g | 1,36E+13 | 2,83E+09 | 3,85E+22 |
| 2 | Steel scrap or slag | g | 3,17E+13 | 2,83E+09 | 8,97E+22 |
| 3 | Post consumer steel collection | g | 1,36E+13 | 2,51E+08 | 3,41E+21 |
| 4 | Post consumer steel separation | g | 1,36E+13 | 8,24E+06 | 1,12E+20 |
| 5 | Natural gas | J | 3,17E+17 | 4,80E+04 | 1,52E+22 |
| 6 | Other fuels | J | 2,80E+16 | 6,60E+04 | 1,85E+21 |
| 7 | Electricity | J | 1,84E+17 | 1,74E+05 | 3,20E+22 |
| 8 | Transportation | ton-mile | 7,50E+09 | 9,65E+11 | 7,24E+21 |
| 9 | Labour | $ | 1,58E+09 | 1,20E+12 | 1,90E+21 |
| 10 | Annual Yield | g | 4,49E+13 | 4,24E+09 | 1,90E+23 |

**Table 3**

| Note Item | Unit/year | Input Resource | Solar emergy per unit (sej/unit) | Emergy (sej/year) |
|---|---|---|---|---|
| **Conventional aluminium sheet production** | | | | |
| Primary aluminium (ingot) | g | 4,17E+11 | 1,17E+10 | 4,88E+21 |
| Electricity | J | 1,08E+15 | 1,74E+05 | 1,88E+20 |
| Labour | $ | 2,09E+07 | 1,15E+12 | 2,40E+19 |
| Annual Yield | g | 4,00E+11 | 1,27E+10 | 5,08E+21 |
| **Recycling Process** | | | | |
| Used aluminium can | g | 2,29E+11 | 1,17E+10 | 2,68E+21 |
| Primary aluminium (ingot) | g | 1,25E+11 | 1,17E+10 | 1,46E+21 |
| Aluminium scrap | g | 6,25E+10 | 1,17E+10 | 7,31E+20 |
| Used Al. can collection | g | 2,29E+11 | 2,51E+08 | 5,75E+19 |
| Used Al. can separation | g | 2,29E+11 | 8,24E+06 | 1,89E+18 |
| Electricity | J | 1,08E+15 | 1,74E+05 | 1,88E+20 |
| Transport (Truck) | ton-mile | 2,82E+07 | 9,65E+11 | 2,72E+19 |
| Labour | $ | 2,90E+07 | 1,15E+12 | 3,34E+19 |
| Annual Yield | g | 4,00E+11 | 1,29E+10 | 5,16E+21 |

**Table 4**

| Note Item | Unit/year | Input Resource | Solar emergy per unit (sej/unit) | Emergy (sej/year) |
|---|---|---|---|---|
| **Conventional plastic product** | | | | |
| Wood fiber | J | 2,67E+12 | 4,20E+04 | 1,12E+17 |
| Plastic resin | g | 7,22E+08 | 5,27E+09 | 3,80E+18 |
| Electricity | J | 1,08E+12 | 1,74E+05 | 1,88E+17 |
| Transport (Truck) | ton-mile | 1,87E+05 | 9,65E+11 | 1,80E+17 |
| Machinery | g | 4,84E+05 | 6,70E+09 | 3,24E+15 |
| Labour | $ | 5,27E+05 | 1,15E+12 | 6,06E+17 |
| Annual Yield | g | 8,50E+08 | 5,75E+09 | 4,89E+18 |
| **Recycling Process** | | | | |
| Post consumer paper | g | 2,67E+12 | 1,42E+05 | 3,79E+17 |
| Post consumer plastic | g | 7,22E+08 | 5,27E+09 | 3,80E+18 |
| Collection | g | 8,49E+08 | 2,51E+08 | 2,13E+17 |
| Separation | g | 8,49E+08 | 8,24E+06 | 7,00E+15 |
| Electricity | J | 1,08E+12 | 1,74E+05 | 1,88E+17 |
| Transport (Truck) | ton-mile | 1,87E+05 | 9,65E+11 | 1,80E+17 |
| Machinery | g | 4,84E+05 | 6,70E+09 | 3,24E+15 |
| Labour | $ | 5,27E+05 | 1,15E+12 | 6,06E+17 |
| Annual Yield | g | 8,50E+08 | 6,33E+09 | 5,38E+18 |

**Table 5**

| | Note Item | Unit/year | Input Resource | Solar emergy per unit (sej/unit) | Emergy (sej/year) |
|---|---|---|---|---|---|
| | **Conventional ceramic tile (glass) product** | | | | |
| 1 | Silica sand | g | 3,38E+09 | 1,00E+09 | 3,38E+18 |
| 2 | Sand | g | 1,31E+08 | 1,00E+09 | 1,31E+17 |
| 3 | Clay | g | 1,09E+09 | 2,00E+09 | 2,18E+18 |
| 4 | Others | g | 2,18E+08 | 1,00E+09 | 2,18E+17 |
| 5 | Water | J | 1,08E+09 | 4,80E+04 | 5,18E+13 |
| 6 | Natural gas | J | 8,85E+13 | 4,80E+04 | 4,25E+18 |
| 7 | Electricity | J | 1,61E+12 | 1,74E+05 | 2,80E+17 |
| | Transport (Truck) | ton-mile | 1,19E+06 | 9,65E+11 | 1,15E+18 |
| | Machinery | g | 4,08E+07 | 6,70E+09 | 2,73E+17 |
| | Labour | $ | 6,85E+05 | 1,20E+12 | 8,22E+17 |
| | Annual Yield | g | 4,14E+09 | 3,06E+09 | 1,27E+19 |
| | **Recycling Process** | | | | |
| 8 | Sand | g | 1,31E+08 | 1,00E+09 | 1,31E+17 |
| 9 | Clay | g | 1,09E+09 | 2,00E+09 | 2,18E+18 |
| | Post consumer glass bottles | g | 2,70E+09 | 1,90E+09 | 5,13E+18 |
| | Others | g | 2,18E+08 | 1,00E+09 | 2,18E+17 |
| 10 | Collection | g | 2,70E+09 | 2,51E+08 | 6,78E+17 |
| 11 | Separation | g | 2,70E+09 | 1,32E+07 | 3,56E+16 |
| | Water | J | 1,08E+09 | 4,80E+04 | 5,18E+13 |
| | Natural gas | J | 6,65E+13 | 4,80E+04 | 3,19E+18 |
| 12 | Electricity | J | 1,21E+12 | 1,74E+05 | 2,11E+17 |
| 13 | Transport (Truck) | ton-mile | 1,19E+06 | 9,65E+11 | 1,15E+18 |
| 14 | Machinery | g | 4,08E+07 | 6,70E+09 | 2,73E+17 |
| 14 | Labour | $ | 6,85E+05 | 1,20E+12 | 8,22E+17 |
| 15 | Annual Yield | g | 4,14E+09 | 3,38E+09 | 1,40E+19 |